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Introduction to the Symposium: '*Ecosystem Studies of Subarctic and Arctic Seas*'

Introduction

Shifting boundaries of water, ice, flora, fauna, people, and institutions in the Arctic and Subarctic

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An international Open Science Meeting entitled Moving in, out, and across the Subarctic and Arctic marine ecosystems: shifting boundaries of water, ice, flora, fauna, people, and institutions, took place 11–15 June 2017 in Tromsø, Norway. Organized by the Ecosystem Studies of Subarctic and Arctic Seas programme and cosponsored by the International Council for the Exploration of the Sea and the North Pacific Marine Science Organization, the primary aim of the meeting was to examine past, present, and future ecosystem responses to climate variability and ocean acidification (OA) and their effect on fishing communities, the fishing industry and fisheries management in the northern Pacific and Atlantic oceans and the Arctic. This symposium issue contains several papers from the meeting covering topics from climate and OA, ecosystem responses to environmental change, and fisheries management including:

- a synthesis of the ecosystem responses to the AMO-linked cold period of the 1970s and 1980s;
- a novel approach to understand responses to OA in northern climes using natural carbonate chemistry gradients, such as CO_2 vents, methane cold seeps, and upwelling area;
- the possibility that warm temperatures are allowing two generations of *Calanus finmarchicus* per year to be produced;
- a new hypothesis suggesting that in areas where sea ice disappears there could be an increase of fish species with swim bladders;
- results from laboratory experiments on the effects of temperature and food on Arctic and boreal fish larvae;
- the application of ecosystem-based management in northern regions; and
- a description of the United States National Oceanic and Atmospheric Administration approach to marine conservation and how it affects fish populations and fisheries.

Keywords: climate change, climate variability, ecosystem responses, fish, fisheries management, ecosystem-based management

Introduction

The 3rd international Open Science Meeting (OSM) organized by the Ecosystem Studies of Subarctic and Arctic Seas (ESSAS) programme and cosponsored by the International Council for the Exploration of the Sea and the North Pacific Marine Science Organization, was held in Tromsø, Norway, on 11–15 June 2017. ESSAS is a regional programme of the Global Change Project IMBeR (Integrated Marine Biosphere Research), which is part of Future Earth. ESSAS was originally established under GLOBEC in 2005 as the Ecosystem Studies of SubArctic Seas to investigate how climate change currently affects, and will affect in the future, marine ecosystems of the SubArctic (Hunt and Drinkwater, 2005a, b). To kick off the program, ESSAS held its first OSM on the "Effects of climate variability on subArctic marine

Ecosystems" in Victoria, Canada in May 2005 (Hunt *et al.*, 2007). Its second OSM entitled "Comparative studies of climate effects on polar and subpolar ocean ecosystems: progress in observation and prediction," was held in Seattle, USA, in May 2011 (Drinkwater *et al.*, 2012; Mueter *et al.*, 2012; Curchitser *et al.*, 2015). By 2011, ESSAS had added the Arctic to its geographic sphere of research, especially focusing upon the interactions between the Arctic and Subarctic. To reflect this increasing work in the Arctic, ESSAS incorporated the word Arctic into its name in 2015 but retained the same acronym. The Arctic work has focused on Arctic gadoids (Mueter *et al.*, 2016) and comparisons among seas within the Arctic (Hunt *et al.*, 2013) and between the Arctic and the Antarctic (McBride *et al.*, 2014; Hunt *et al.*, 2016; Murphy *et al.*, 2016).

Increases in the air and sea temperatures in the Arctic during the last couple of decades have resulted in a significant decline in summer sea-ice cover in the Arctic Ocean, changes in the timing of ice retreat in the spring and of ice formation in the fall, decreases in the thickness of the ice and the loss of multiyear ice (IPCC, 2013; Screen, 2014). In the Subarctic Seas, there have also been large changes in sea temperatures but with important spatial variability. For example, generally warm conditions have been observed in the Barents and Nordic Seas of the North Atlantic (Smedsrud *et al.*, 2013) while in the Bering Sea, temperature conditions have varied between warm and cold periods with corresponding decreases and increases in winter sea-ice cover, respectively (Stabeno *et al.*, 2012). These changes in the water and ice properties have resulted in changes in the biogeochemistry and ecology of these regions (Hunt *et al.*, 2011; Johannesen *et al.*, 2012) including increased ocean acidification (OA; Browman, 2017) and the expansion northward of many species of plankton and fish (Sigurjónsson, 2016). Growth rates, recruitment levels, and phenology are also changing, resulting in increased abundances of some species and decreases in others. Changes in distribution and abundance of fish populations have resulted in changes in fisheries. For example, in some areas expanding populations have resulted in the development of new fisheries or the expansion of existing fisheries, while the loss or contraction of traditionally harvested stocks in other areas has caused those fisheries to disappear. This has resulted in difficulties with fisheries management based on historical fishing rights, e.g. Atlantic mackerel in the North Atlantic (Hannesson, 2016). These are all issues of concern, especially to northern nations.

To address some of these issues, the 3rd ESSAS OSM was entitled *Moving in, out and across the Subarctic and Arctic marine ecosystems: shifting boundaries of water, ice, flora, fauna, people, and institutions*. Its main objectives were (i) to document changes that have occurred in Subarctic and Arctic marine ecosystems during the past century and the processes that led to these changes, especially those related to climate including anthropogenic climate change and OA; (ii) to compare and contrast the changes and processes in the North Atlantic, North Pacific, and Arctic; (iii) to place what is happening today in a longer-term perspective by examining the paleo-ecology of ecosystems and people in Subarctic and Arctic regions related to changing temperature and sea-ice conditions over time scales of millennia to centuries; (iv) to discuss how future changes are likely to further affect these ecosystems; (v) to determine how humans who depend upon these ecosystems will cope with the expected changes in the goods and services they derive from these ecosystems including the opportunities for commercial fishing; and (vi) to study the consequences of economic and societal pressures to coastal communities and nations as a result of these ecosystem changes.

The first day of the OSM included a series of four topical workshops on: Paleo-Ecology of Subarctic and Arctic Seas (PESAS); Climate change impacts on nearshore fish habitats in the Arctic; Using natural analogues to investigate the effects of climate change and OA on northern ecosystems; and Arctic and Subarctic climate change impacts: a transdisciplinary perspective (see Supplementary Material). These were followed by nine theme sessions through the week, including: PESAS; Advection and mixing and their ecosystem impacts; Timing/phenology and match–mismatch: are they critical issues?; Shifting habitats, persistent hot spots; Future Subarctic and Arctic marine ecosystems under climate change; Multiple stressors; Ocean acidification; Science, Policy and Management; and a General Open Session (see Supplementary Material for the program). A total of 187 scientists from 17 countries attended the OSM.

Highlights of the articles appearing in this symposium issue

The present issue includes 11 papers from the OSM on a variety of topics from climate and OA to fish, fisheries and fisheries management.

One of the major climate indices in the Atlantic Ocean is the Atlantic Multidecadal Oscillation or AMO, which has a periodicity of ∼60–80 years. It is defined as the detrended North Atlantic sea surface temperature anomalies from the equator to 60°–70°N. AMO-like variability also extends farther north into the Barents Sea and the Arctic. Several studies have documented the ecosystem responses to the mid-20th Century warm period in the North Atlantic associated with the AMO and the recent warming. Drinkwater and Kristiansen (2018) provide a synthesis of the ecosystem responses to the AMO-linked cold period of the 1970s and 1980s following the rapid cooling in the 1960s. This and other cold periods have received much less attention in the scientific literature. During this period, below average air and sea temperatures, expanded sea-ice cover and reduced Atlantic inflow into the Northeast Atlantic Ocean led to decreased primary production, a general southward expansion of arctic and boreal zooplankton and fish species, and a southward retreat of temperate species. The Atlantic cod fishery off Greenland and Labrador/northern Newfoundland and the Norwegian spring-spawning herring off Iceland and Norway collapsed, driven in part by climate-induced declines in growth rates and recruitment. However, intense fishing also played a role in the collapse of these highly valued fish stocks. At the extreme southerly limits of Atlantic cod, such as the North Sea, this species experienced the opposite response as the cool conditions led to improved growth rates and higher recruitment. Distributional shifts and changed abundances also occurred for benthic species and seaweeds. Following the cold period, as the temperatures warmed in the 1990s and 2000s, the ecosystem mainly returned to conditions like those in the warm mid-20th Century. However, this was not true for some species such as Atlantic cod off West Greenland and Labrador/northern Newfoundland, which never recovered. The authors conclude that the primary mechanism through which temperature acts on fish is through its influence on food availability. Understanding the ecosystem response to the AMO variability that is expected to continue into the future, together with anthropogenic climate change, will allow us to anticipate what changes might occur during any prolonged future cooling period and hopefully lead to better management practices.

In addition to climate change, acidification of the world's oceans is occurring at a rapid rate, with some of the largest changes in the Arctic and other cold water regions. This is expected to have important effects on the physiology of many species and may change the dynamics of some populations and the function and structure of some ecosystems. Our understanding of the effects of OA on Arctic and subArctic ecosystems is limited and has until now relied on short-term single-species laboratory studies. Rastrick *et al.* (2018) propose a novel approach to understand potential responses to OA in northern climes that has not been undertaken in these regions. They review the use of natural carbonate chemistry gradients in tropical and temperate regions, such as around hydrothermal vents, to learn about long-term acclimation and adaptation to elevated levels of pCO_2. The authors suggest future OA-focused field studies and monitoring of organisms around CO_2 vents, methane cold seeps, estuaries, upwelling areas and fronts in the Arctic and subArctic that contain gradients of pH, carbonate saturation state, and alkalinity. These, in combination with experimental in situ and laboratory studies, would lead to improved predictions of OA impacts on high latitude species and ecosystems.

Aarflot *et al.* (2018) examine the variability of mesozooplankton in the Barents Sea and its relation to environmental conditions from data collected over 30 years. They find that 80% of the variation is from three *Calanus* species (*C. finmarchicus*, *C. glacialis*, and *C. hyperboreus*). Whereas all three species co-occur to some degree, *C. finmarchicus* dominates in the Atlantic waters and *C. glacialis* in the Arctic waters. *Calanus hyperboreus* is the least abundant of the three species and has the lowest biomass despite a much larger body size per individual. The biomass of the Arctic *C. glacialis* has been decreasing over the last two decades or more while *C. finmarchicus* has been increasing. The authors suggest that these changes are related to warming ocean temperatures and provide additional evidence of the borealization of the zooplankton community in the Barents Sea. They further speculate that the large increase in *C. finmarchicus* may be because the recent very warm temperatures are allowing two generations per year to be produced, as opposed to the one generation per year in earlier, cooler years. The authors also speculate that the increase in the abundance of the smaller size *C. finmarchicus* may be detrimental for some higher trophic levels, e.g. fish, marine mammals and seabirds, due to less efficient energy transfer.

Skogen *et al.* (2018) investigate the possible future primary productivity in the Nordic and Barents seas through comparing the results from a global climate model (Norwegian Earth System Model) with that from a higher resolution regional model (NORWECOM.E2E) over the period 2006–2070. The regional model is forced by downscaled physics from the global model under RCP4.5. The Gross Primary Production (GPP) is significantly higher in the regional model as the global model predicts much higher sea-ice concentrations, which reduces light levels and delays the spring bloom by 1–2 months, hence lowering the GPP estimates to below observed levels. The lower GPP in the global model also results in less utilization of nutrients as not all surface nutrients were used up during the production season. Relative to climatology, the global model has a cold (in summer) and saline bias owing to poorly resolved physical processes and oversimplified ecosystem parameterization. Through downscaling, the regional model is, to some extent, able to alleviate the bias in the physical fields, and the timing of the spring bloom is close to observations. However, the summer nutrient minimum is one month earlier than observed. There is no trend in future primary production in either model and the trends in modelled pH and Aragonite are the same in both models. The largest discrepancy in the future projection is in the development of the CO_2 uptake, where the regional model suggests a slightly reduced uptake in the future. On the basis of comparisons with observations, the regional model outperforms the global model.

Kaartvedt and Titelman (2018) discuss mechanisms related to the variability in the geographical distribution of fish and plankton, including one that has been seldom raised. Fish possessing swimbladders need to reach the surface to take in air, which allows them to control their buoyancy. Since sea-ice coverage limits access to the surface, the authors hypothesize that present and projected continuing reduction in ice coverage might lead to the northward expansion of such fish species and would also impact their zooplankton prey. Another mechanism the authors discuss is the effects of the extreme high-latitude photoperiod. Noting the low abundance of mesopelagic fish in the Arctic Ocean, they suggest that this might be because of poor feeding conditions during winter darkness and light summer nights. If light levels are indeed the main limitation on determining geographical distribution, this would suggest that warming temperatures under climate change may not have any effect on mesopelagic fish in the Arctic. However, if temperatures control their geographical boundaries, an invasion of mesopelagics from the south into the Arctic under warmer conditions may reduce key Arctic copepods through increases in predation rates. Resolving the main mechanism (light vs. temperature) producing geographical extensions or shifts is, therefore, vital to improving projections of future biogeographic boundary changes.

Invasions of boreal fish species into the Arctic are projected to occur under increasing sea temperatures and declining sea ice. There are educated guesses on the future of these invasive species as well as resident Arctic fish, but these are subject to large uncertainties due to a general lack of information on issues such as their thermal tolerance and ability to cope with changing trophic interactions. To address such issues, a series of three papers based on experimental laboratory studies of eggs and larvae compares the responses to environmental variability of an Arctic gadid (Arctic cod, *Boreogadus saida*) and a boreal gadid (walleye pollock, *Gadus chalcogrammus*). Koenker *et al.* (2018a) investigate the influence of temperature and food on the energetic condition of the larvae of the two species that is closely associated with mortality rates and, therefore, provides an indicator of overall well-being or fitness of the fish. The authors find that the effect of both temperature and food varies with species and ontogenetically. Condition in first-feeding Arctic cod larvae peaks at colder temperatures (2–5°C) than for pollock (5–12°C). At later larval stages, peak condition for Arctic cod occurs at warmer temperatures (7°C), while for pollock the thermal optimum is not stage dependent. Arctic cod are more sensitive to food ration at first feeding than walleye pollock, however; at later larval stages both species have a negative condition response to low food ration, especially at elevated temperatures (5° vs. 7°C). The lower thermal tolerance of Arctic cod, coupled with a higher sensitivity to food availability indicates that Arctic cod are particularly vulnerable to on-going environmental change. Arctic cod is a lipid-rich keystone species and, therefore, a reduction in their energetic condition during summer has the potential to affect the health of higher trophic levels such as predatory fish, marine mammals and seabirds throughout the Arctic. In a second laboratory study involving the same two cod species, Koenker *et al.* (2018b) investigate the effects of temperature and food availability on survival and growth of larvae. At low temperatures, Arctic cod larvae are better adapted than walleye pollock in terms of growth and survival but under warmer, high food rations, walleye pollock have the advantage, exhibiting higher growth and better survival. The authors also find that the thermal response in the larvae is both species- and stage-dependent. Laurel *et al.* (2018) incubated multiple batches of gadid eggs and larvae from laboratory broodstock held under simulated seasonal environmental conditions for the species investigated. Arctic cod eggs and larvae were ∼25–35% larger than walleye pollock with 3–6× more energetic reserves. A low thermal tolerance is similar for both species but Arctic cod have a much lower upper thermal tolerance. While this means that Arctic cod have a much smaller thermal window for survival, they can survive for longer periods in the absence of food than can walleye pollock at cold temperatures. The new information on vital rates from all three studies provides a mechanistic framework for understanding potential spatial-temporal shifts of these gadids at the boundary between the Arctic and subArctic resulting from climatic warming and altered productivity regimes by supporting better population forecasts, species distribution models and biophysical transport models for these species.

Eggs and larvae of zooplankton and fish are transported by ocean currents, which influence their spatial distribution and survival. Kvile *et al.* (2018) use a biophysical model of the North Sea cod (*Gadus morhua*) to explore the relative importance of model resolution, the vertical behaviour of the eggs and larvae and interannual variability in water circulation and temperature on the distribution and survival of cod. Vertical movement and ocean model resolution both influence the results moderately but their effects differ substantially between years. Generally, higher ocean model resolution has a larger effect than changes in the vertical behaviour of the cod larvae.

Merrick (2018) describes the United States National Oceanic and Atmospheric Administration (NOAA) approach to marine conservation and its effects on fish populations and fisheries. The management advice must be strongly science-based. Legislative mandates require that marine resources and their habitats be protected to provide productive and sustainable fisheries, safe sources of seafood, the recovery and conservation of protected resources, and healthy ecosystems. In response, NOAA implemented a four-pronged approach: (i) the development of a national framework for conservation science, (ii) implementation that is region-specific, (iii) development of unbiased, scientific advice, and (iv) scientists acting as advocates and science communicators. This approach has been successful with 92% of managed fish stocks no longer being overfished and 84% of stocks that are assessed being at healthy levels. Forty-three of the latter are stocks that have been rebuilt from low or depleted levels. The author argues that it is vitally important that marine conservation decisions everywhere be science-driven, particularly under climate change.

Unprecedented and rapid changes are ongoing in northern high-latitude marine ecosystems, due to climate warming. Species distributions and abundances are changing, altering both ecosystem structure and dynamics. At the same time, human impacts are increasing. Less sea ice opens the door for more petroleum-related activities, shipping and tourism. Fisheries are moving into previously unfished habitats, targeting more species across more trophic levels. Skern-Mauritzen *et al.* (2018) argue that there is a need for Ecosystem Based Fisheries Management (EBFM) and Ecosystem Based Management (EBM) to take the rapid, climate driven changes more fully into account. Recently, there has been much development in qualitative, semiquantitative and quantitative scientific approaches to support EBFM and EBM. They present some of these approaches and discuss how they provide opportunities for advancing EBFM and EBM in the Barents Sea. The authors propose that advancing EBFM and EBM is more about adding tools to the toolbox than replacing tools, and to use the tools in coordinated efforts to tackle the increasing complexities in scientific support for decision making. Collaborative and participatory processes among managers and scientists are pivotal for both scoping and prioritizing, and for efficient knowledge exchange.

Summing up and future work

Collectively, the above papers represent a glimpse into some of the important issues that the ESSAS programme is addressing. They represent retrospective analyses to understand climate effects on marine ecosystems at long and short time scales and from basin to local geographic scales within the Pacific, Atlantic, and Arctic oceans. Major work is ongoing to understand the mechanistic processes linking climate and ecological variability, including laboratory studies that provide parameters and vital rate information for use in models. Such models are also being used to develop future climate and ecosystem scenarios under anthropogenic climate change and OA. Finally, an important aspect of ESSAS research is the linking of the research to fisheries and ecosystem-based management. Some future work that is planned: development of climate change and ecosystem scenarios in the transition zone between the Subarctic and the Arctic; paleo-ecology studies linking ocean productivity to the timing of the establishment of human settlements, both prehistoric and historic, and fluctuations in the settlement population levels; studies of the life cycle and the mechanisms controlling the distribution and abundance of Arctic/Polar cod (*B. saida*); comparisons of management strategies of different nations with respect to their preparedness to meet the challenges of climate change and OA; and an exploration of the use of natural analogues to investigate the effects of climate change and OA on northern ecosystems. Strategically, longer-term goals are (i) to engage in more socio-ecological studies that consider not only the natural environment but also the effect of and on humans, (ii) to quantify the uncertainty in future projections of ecological changes, and (iii) to increase our mechanistic understanding of factors influencing fish population variability in northern regions as input to management of sustainable fisheries.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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